**APPENDIX A. U.S. DEPARTMENT OF ENERGY COVER PAGE FOR SMALL BUSINESS INNOVATION RESEARCH (SBIR) AND SMALL BUSINESS TECHNOLOGY TRANSFER (STTR) PROGRAMS**

**SOLICITATION NO. DOE/SC-0039**

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|---|---|

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**PROJECT**

**TITLE:** **Pressurized RF Cavities for Muon Ionization Cooling**

Topic No. (1-45): 21 | Subtopic (a-d): a

Amount Requested (not to exceed $100,000): $ 100,000

**SMALL BUSINESS**

FIRM NAME: MUONS INC.

I.R.S Entity Identification or SSN: 341 44 5746

ADDRESS: 552 N. Batavia Ave.
CITY: Batavia STATE: IL ZIP 60510

| Principal Investigator (See Requirements in Sec. 1.5) | Corporate/Business Authorized Representatives |
|---|---|
| Dr. Rolland P. Johnson | Linda L. Even |
| Title: Scientist Phone Number: (757) 930 1463 | Title: Owner/CEO Phone Number: (630) 879 0721 |
| E:mail address: roljohn@aol.com | E:mail address: lle452b@aol.com |

**Certification and Acceptance:** I certify that the statements herein are true and complete to the best of my knowledge, and accept the obligation to comply with DOE terms and conditions if an award is made as the result of this submission. A willfully false certification is a criminal offense. (U.S. Code, Title 18, Section 1001)

**Signature:** **Date:** **Signature:** **Date:**

**RESEARCH INSTITUTION**

Check YES or NO: This grant application contains substantial collaboration with a research institution (see definition Sec. 2.8 and Sec. 1.5.3).

X YES NO

Check one: This application should be considered for:
SBIR only.
STTR only.
X both SBIR and STTR.

NAME OF RESEARCH INSTITUTION: Illinois Institute of Technology

$_33,000_Amount of Subcontract

ADDRESS:
3300 South Federal Street
CITY: Chicago STATE: IL ZIP 60616-3793

Certifying Official: Ms. Mary Spina

Title: Director, Office of Sponsored Research
Phone Number: (312) 567-3035
e-mail address: spina@iit.edu

**Certification:** If this grant application is selected for award, I certify that the above research institution will conduct the work herin attributed to it.

**Signature:** **Date:**

**OTHER SUBCONTRACTORS: INDICATE NAME AND DOLLAR AMOUNT**

**CERTIFICATIONS AND QUESTIONS: ANSWER Y (YES) OR N (NO)**

Y 1. The above applicant organization certifies that it is a small business and meets the definition stated in Section 2.3.

Y 2. The applicant small business will comply with the provisions regarding: (1) lobbying, (2) debarment, suspension, and other responsibility matters, and (3) drug-free workplace requirements. (See Certifications Section.) Inability to certify to any or all statements requires explanation.

Y 3. The Principal Investigator will have his/her primary employment with the small business at the time of award (see Section 1.5.2).

N 4. Has the firm and/or Principal Investigator submitted proposals containing a significant amount of essentially equivalent work under other federal program solicitations, or received other federal awards containing a significant amount of essentially equivalent work? **If "yes", the application must include the required information requested in Section 3.3.4.**

N 5. Is the small business delinquent on any Federal debt? (If "yes," please attach an explanation.)

Y 6. If the proposed project does not result in an award, does the applicant permit the government to disclose the technical abstract of the application, and the name, address, and telephone of the business official to any inquiring parties?

**PROPRIETARY NOTICE (SECTION 5.4)** For any purpose other than to evaluate this submission, these data shall not be disclosed outside the Government and shall not be duplicated, used, or disclosed in whole or in part, provided that if a grant is awarded to this applicant as a result of or in connection with the submission of these data. The Government shall have the right to duplicate, use, or disclose the data to the extent provided in the grant. This restriction does not limit the Government's right to use information contained in the data if it is obtained from other source without restriction. The data in this submission subject to this restriction are contained on pages ________________

U.S. DEPARTMENT OF ENERGY **APPENDIX B**
**SMALL BUSINESS INNOVATION RESEARCH PROGRAM**
**SMALL BUSINESS TECHNOLOGY TRANSFER PROGRAM**
**SOLICITATION NO. DOE/SC-0039**
**PROJECT SUMMARY**
**Phase I**

| DOE USE ONLY | - 02 -I |
|---|---|

| **21** | **a** |
|---|---|
| Topic No. (1-45) | Subtopic (a-d) |

**(All information provided on this page is subject to release to the public.)**

| **FIRM NAME:** **MUONS INC.** | **RESEARCH INSTITUTION:** **Illinois Institute of Technology** |
|---|---|
| ADDRESS: 552 N. Batavia Ave., Batavia, IL 60510 | ADDRESS: 3300 South Federal Street, Chicago, IL 60616-3793 Tel 312 567-3000 |

NAME of PRINCIPAL INVESTIGATOR: Dr. Rolland P. Johnson PHONE NUMBER: (757) 930 1463

PROJECT TITLE: **Pressurized RF Cavities for Muon Ionization Cooling**


TECHNICAL ABSTRACT (Limit to space provided)

Statement of the problem or situation that is being addressed - typically, one to three sentences.

Ionization cooling, a method for shrinking the size of a particle beam, is an essential technique for future particle accelerators that use muons. Future Muon Colliders and Neutrino Factories, examples of these accelerators, require high voltage radio frequency (RF) cavities for ionization cooling.

General statement of how this problem is being addressed. This is the overall objective of the combined Phase I and Phase II projects - typically, one to two sentences.

Unlike any previous particle accelerator, muon beams in an ionization cooling channel are not only allowed but are required to be accelerated through an energy absorbing material. This proposal is to develop very high voltage RF cavities by filling them with cold, pressurized helium or hydrogen gas, which also acts as the energy absorber, to suppress high-voltage breakdown.

What is planned for the Phase I project (typically, two to three sentences).

The primary goal of Phase I is to build an RF test cell suitable for testing the breakdown characteristics of gases to be used in ionization cooling applications. The test cell will allow the exploration of Paschen’s Law, relating breakdown voltages to gas density, over a range of temperatures, pressures, external magnetic fields, and ionizing particle radiation.


COMMERCIAL APPLICATIONS AND OTHER BENEFITS as described by the applicant. (Limit to space provided).

The estimated cost of the ionization-cooling component of each muon collider or neutrino factory is roughly $350 million. If this project is completely successful, the voltage of the RF cavities used in these applications could be increased significantly, which would lead to a correspondingly shorter cooling channel and smaller cost. Discussions have started with commercial accelerator vendors regarding producing pressurized RF cavities for profit.

SUMMARY FOR MEMBERS OF CONGRESS: (LAYMAN'S TERMS, TWO SENTENCES MAX.)

Neutrino Factories and Muon Colliders, new kinds of particle accelerator needed for tomorrow’s studies of the fundamental forces of nature, require a technique to shrink a beam of muons before it can be accelerated. A new idea only available to muon accelerators is being developed to use cold, pressurized gas to allow higher accelerating fields to reduce a muon beam size faster and cheaper.

## Pressurized RF Cavities for Muon Ionization Cooling

## Table of Contents



## Significance and Background Information, and Technical Approach

### Identification of Problem

Future research facilities, such as Neutrino Factories[i] or Muon Colliders[ii], which require intense beams of muons, are dependent on a scheme to quickly reduce or cool the emittance of a muon beam before it can be injected into a practical accelerator. Ionization cooling is the scheme favored by the Neutrino Factory and Muon Collider Collaboration (NFMCC)[iii], used in Neutrino Factory Design Studies by Fermilab[iv], Brookhaven[v], and Europe[vi], and the object of study in the International Muon Ionization Cooling Experiment (MICE)[vii]. Ionization cooling, as envisioned in these works, involves passing the muon beam down a tightly focused magnetic channel consisting of RF accelerating cavities and liquid hydrogen energy absorbers. The theory of this process is straightforward and can be found in many references[viii].

The muon beam to be cooled is a secondary beam, produced primarily by the decay of pions, and is therefore large in all dimensions. Consequently the channel accelerating structures must have large acceptance, both transversely and longitudinally. Thus the RF cavities of choice have large apertures and correspondingly low frequencies (88MHz at CERN and 200MHz in the US) and as large a voltage gradient as possible subject to limits of power sources and electrical breakdown.

These are difficult parameters for RF systems and most designs referenced above assume a maximum gradient of about 10 MV/m on axis.

The gradient provides the compensation for the energy lost by the muons in the hydrogen absorbers and also provides the momentum acceptance to capture and hold the muons. Roughly speaking, the gradient is split equally for these two functions. Since the energy absorption of liquid hydrogen is 30 MeV/m, to be compared with an effective accelerating voltage of less than 5 MeV/m, it is easy to see why the RF cavities determine the length of the channel.

And that is the problem. The studies so far have shown that the cost of the channel is dominated by the cost of the RF systems themselves and the cost of the superconducting solenoidal magnets, both of which scale with the length of the channel. Approximately, if the gradient of the RF cavities could be doubled, the length and corresponding cost of the channel could be halved.

Another problem is that the RF cavities in the Fermilab and Brookhaven cost estimates are a closed-cell design with thin beryllium windows used to lower the voltage maxima within the cavity, allowing higher gradients. The practical problems of dealing with the heat flow in the thin beryllium windows and their temperature-induced distortions are yet to be solved. Thus there is a cost uncertainty in the estimates related to finding a way to remove the heat from the beryllium windows.

**Significance**

In the Brookhaven and Fermilab studies, ionization cooling increases the density of muons within the useful phase-space and improves the Neutrino Factory performance by a factor of 4 to 10 depending on the specific design. This reduces the cost of the accelerating devices. However, the ionization-cooling channel itself is expensive, representing as much as 20% of the Neutrino Factory cost estimates, as shown in Table 1 from the Brookhaven study.

| System | Sum ($M) | Others[a] ($M) | Total ($M) | Reconciliation[b] (FY00 $M) |
|---|---|---|---|---|
| Proton Driver | 167.6 | 16.8 | 184.4 | 179.9 |
| Target Systems | 91.6 | 9.2 | 100.8 | 98.3 |
| Decay Channel | 4.6 | 0.5 | 5.1 | 5.0 |
| Induction Linacs | 319.1 | 31.9 | 351.0 | 342.4 |
| Bunching | 68.6 | 6.9 | 75.5 | 73.6 |
| Cooling Channel | 317.0 | 31.7 | 348.7 | 340.2 |
| Pre-accel. linac | 188.9 | 18.9 | 207.8 | 202.7 |
| RLA | 355.5 | 35.5 | 391.0 | 381.5 |
| Storage Ring | 107.4 | 10.7 | 118.1 | 115.2 |
| Site Utilities | 126.9 | 12.7 | 139.6 | 136.2 |
| Totals | 1,747.2 | 174.8 | 1,922.0 | 1,875.0 |

*Table 1: Summary of Construction Cost Totals for Study-II Neutrino Factory.*

Roughly speaking, a factor of two improvement in RF gradient for the cooling channel cavities could save $170 million in this estimate. Additionally, if a sure way to remove heat from the beryllium windows of the cavities were found, the cost estimates in the table would be more reliable. Another benefit, which must be confirmed by simulation, is that a more compact cooling channel would be more efficient at ionization cooling.

**Opportunity**

Using the general parameters of the cooling channels described of the design studies, it is possible to replace the liquid hydrogen absorbers with a continuous gas absorber with sufficient density to provide the same total energy loss. This idea is attractive because it eliminates the technically challenging liquid hydrogen absorbers with their containers that degrade the ionization cooling and cause muon losses.

Two rather independent ideas have come together to make the use of a gaseous absorber for ionization cooling an attractive alternative to the liquid absorber schemes. The first is that the density of gas needed for energy absorption is sufficient to suppress RF breakdown, as described by Paschen's Law[ix]. The idea is really quite novel for particle accelerators, namely that there is a regime where an RF cavity can operate in the high-density side of the Paschen curve. Of course, this is only possible for muons, which do not interact strongly as do protons, or easily lose energy by radiation, as do less-massive electrons. The second observation is that a solenoidal cooling channel can be designed such that the beam is tightly focused along its entire length[x]. In this case, there is no need to concentrate the absorber at the periodic low-beta sections of the channel as in the NFMCC designs.

The first opportunity addressed in this proposal is that it is possible to extend the use of Paschen's Law to even higher gradients. As is discussed below, Paschen's Law shows the breakdown voltage of hydrogen gas in the region of interest increases approximately as density to the 3/2 power. Of course the energy loss for ionization cooling increases with gas density, as does the corresponding required accelerating gradient. Thus the ratio of breakdown voltage to the required accelerating voltage increases as the square root of gas density. Consequently, the higher the density, the more favorable the conditions are for ionization cooling.

The second opportunity is related to the amazing property of copper that its resistivity decreases dramatically with temperature. Copper resistivity falls by a factor of 8 as its temperature is reduced from 300K to 80K[xi], the temperature of liquid nitrogen. At 30K, copper resistivity is a factor 240 less than at 300K.

The RF system designs of the Fermilab and Brookhaven studies are limited by the available klystron power. Except for the question of the design of the closed cell structures using thin beryllium windows, the improvement of electrical breakdown is not so important as long as the power is limited. Operating the cavities at 80K reduces the RF power requirements by a factor of the square root of 8. This assumes no anomalous skin depth effect and no resistivity dependence on the external magnetic field, both assumptions to be verified. Alternatively, using the same power supply costs as in the design studies, and assuming Paschen's law for breakdown suppression, the gradient could be increased by 68%. This is a goal for Phase II.

**We propose to develop a high gradient RF cavity, operating in high-pressure hydrogen at low temperature, which will significantly improve the performance and reduce the cost of a muon ionization-cooling channel.**

Besides the shorter channel and reduced costs, there are two additional benefits to operating the cavities filled with high-density gas. The first is that there are two possible solutions to the problem of the high voltages induced in the RF cavities associated with present cooling channel designs. As mentioned above, the closed-cell design using beryllium windows to smooth the voltage profile within the cavity lacks a convincing method to keep the RF windows from heating and flexing. We believe that the high heat capacity of hydrogen gas can be used to keep the beryllium windows of closed-cell cavities from overheating. In this case the widows will be grids with many holes to allow the dense gas to freely circulate throughout the cooling channel. A second, simpler solution is just to forgo the windows, allow the unfavorable voltage profile, and suppress breakdown with the high-pressure gas.

The second additional benefit of the dense gas is the suppression of dark currents and any other avalanche phenomena. The instrumentation inside the cooling channel to measure the properties of the muon beam will be sensitive to the intense radiation normally generated by high-gradient RF cavities. We believe Paschen's law applies to this problem as well, and more detector options will be available as a result of operation in a dense gas.

## Technical Approach

### Paschen's Law

Most RF cavities associated with particle accelerators operate in as good a vacuum as possible to avoid electrical breakdown. In a good vacuum, electrons or ions that are accelerated by the high voltages in the RF cavity rarely encounter atoms of the residual gas, and so the avalanche process of breakdown is inhibited. Other RF systems that do not require the ultrahigh vacuum of an accelerator typically suppress RF breakdown by using dense materials between electrodes. Ions passing through these materials, which include high-pressure and/or high-density gases, have such a short mean free path between collisions that they do not accelerate to energies high enough to create an avalanche. The relationship between the electrical breakdown voltage and the pressure times gap width is known as Paschen's Law[xii].

Figure 1 shows the theoretical and experimental Paschen curves for hydrogen gas at 2.8 GHz near the minimum in breakdown voltage. Breakdown voltages increase to the left as the pressure decreases and they also increase to the right as the pressure increases. Measurements exist for the static case in gaseous hydrogen for pressures up to about 25 atmospheres as shown in figure 2, where the data are compared to the expression[xiii]

$$V_s = 0.448\,(nd) + 0.6\,(nd)^{1/2},$$

where $V_s$ is the static breakdown voltage in kV, $n$ is the number density of atoms or molecules in units of $10^{18}$ cm$^{-3}$, and $d$ is the separation in cm.

While the exact value of a breakdown voltage will depend on many parameters, such as RF frequency, surface condition, and external magnetic field, we can use Paschen's Law as a first approximation. From this expression we see that above a pressure of about 40 atmospheres at room temperature, gradients in excess of 50 MV/m can be supported. Since density is the actual variable of merit for suppressing breakdown, a lower temperature and pressure can also be used for ease of engineering, since the density is proportional to PV/T. For the parameters of the Fermilab and Brookhaven cooling channels, the density of hydrogen needed to provide the energy loss for ionization cooling is over twice that needed to suppress electrical breakdown.

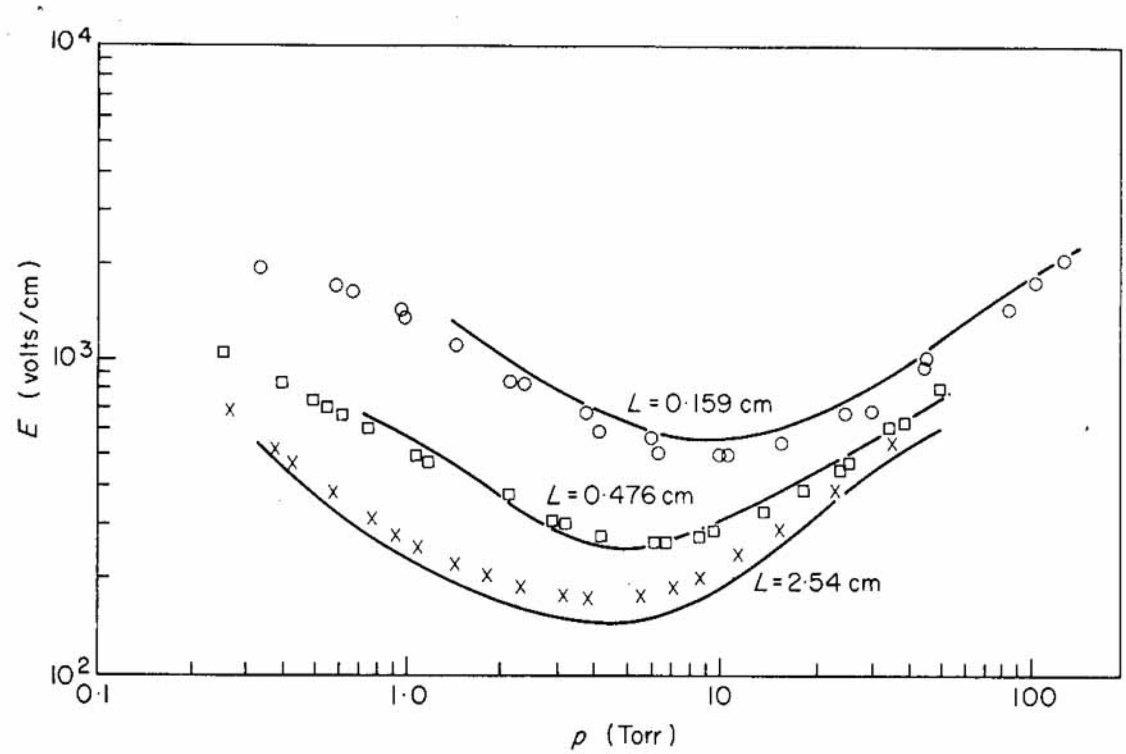
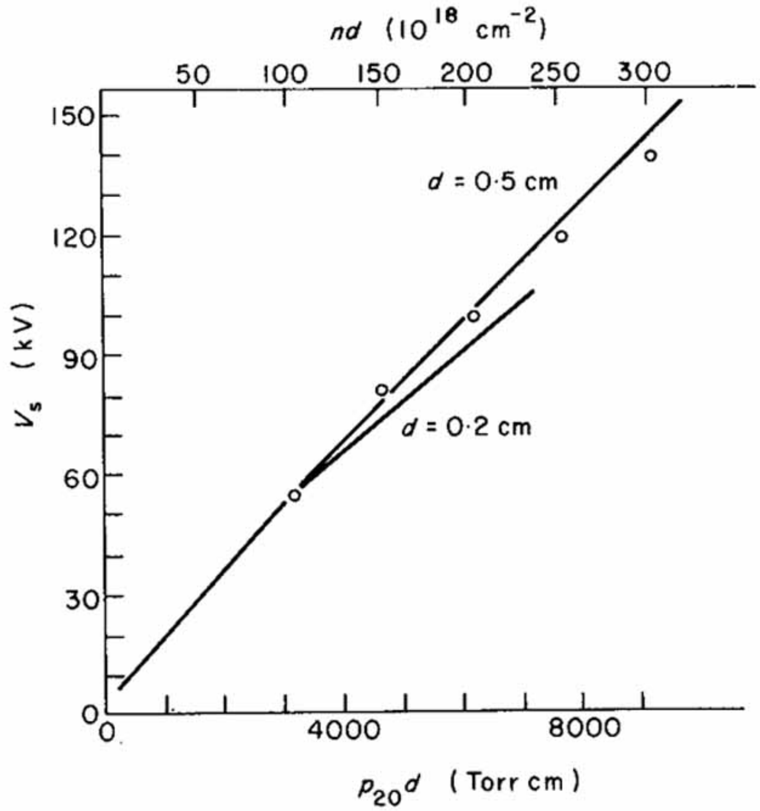



**Figure 8.13**. Theory and experiment compared for hydrogen at 2·8 GHz (MacDonald and Brown, 1949. Reproduced by permission of The America Physical Society)

**Figure 1. Minimum of Paschen Curve for Hydrogen at 2.8GHz**




Breakdown voltages in hydrogen (Müller, 1966. Reproduced by permission of Springer–Verlag)

—— Müller (1966)

O Félici and Marchal (1948)

**Figure 2. High-Pressure Side of Paschen Curve for Hydrogen**

**Low Temperature Operation and Copper Resistivity**

Low temperature operation of RF cavities has been suggested in the past, even for muon ionization cooling. Table I shows the resistivity of pure, annealed of copper[xiv] and the relative resistivity normalized to the resistivity at 300K as a function of temperature.

For ionization cooling systems such as the Fermilab, Brookhaven, and MICE designs, which are RF power limited, a way to improve the gradient is to lower the power requirements by lowering the temperature to reduce the copper resistivity. The availability of cheap liquid nitrogen in large quantities makes the choice of 80K and the corresponding resistivity reduction of a factor of 8 very attractive. However, as the table shows, there is a very large drop in resistivity as the temperature is lowered further. One aspect of the phase II study will be to determine the optimum temperature for operation in a muon ionization-cooling channel, considering costs of construction and operation. Hydrogen has a critical temperature of 33.2 K and critical pressure of 26.3 atm, which gives an approximate lower bound of 30K on the temperature to be considered for the proposed application.

TABLE 1. Resistivity of Copper

| T (K) | Resistivity 10^(-8) Ohm-m | Ratio |
|---|---|---|
| 1 | 0.002 | 862.50 |
| 1 0 | 0.00202 | 853.96 |
| 2 0 | 0.0028 | 616.07 |
| 4 0 | 0.0239 | 72.18 |
| 6 0 | 0.0971 | 17.77 |
| 8 0 | 0.215 | 8.02 |
| 1 0 0 | 0.348 | 4.96 |
| 1 5 0 | 0.699 | 2.47 |
| 2 0 0 | 1.046 | 1.65 |
| 2 7 3 | 1.543 | 1.12 |
| 3 0 0 | 1.725 | 1.00 |
| 4 0 0 | 2.402 | 0.72 |
| 5 0 0 | 3.09 | 0.56 |
| 6 0 0 | 3.792 | 0.45 |
| 7 0 0 | 4.514 | 0.38 |
| 8 0 0 | 5.262 | 0.33 |
| 9 0 0 | 6.041 | 0.29 |

The surface resistance, $R_S$, the relevant quantity for power and voltage considerations, is the resistivity, $\rho$, divided by the skin depth, $\delta_S = (\rho/\pi\mu f)^{1/2}$. Thus $R_S = (\pi\mu f\,\rho)^{1/2}$. Two complications to this relationship are the effects of an external magnetic field and of the anomalous skin depth[xv], which will be subjects of investigations during Phase II. Magnetostrictive increase of the surface resistivity due to the external solenoidal field is expected to be less than 10% and somewhat dependent on the placement of the coils. The anomalous skin depth effect seems to be small at our proposed temperatures and frequencies.

At very low temperature in the extreme anomalous conduction region, where the mean free path of the conduction electrons become very large compared with the skin depth, the surface resistance of the conductor becomes independent of the d.c. conductivity and scales as frequency to the 2/3 power[xvi]. Data taken by R. G. Chambers[xvii] and E. Tanabe[xviii] on copper at 80K show some anomalous behavior at 1.2 GHz and more at 3.0 GHz. At 80K, copper is not anomalous at 805 MHz or 200 MHz, so improvement factors of about 3 in surface resistance are to be expected.

The data of Chambers show that in the extreme anomalous region, a factor 6 improvement of the surface resistance of copper at 1.2 GHz at 30 K. Using the above scaling we could expect a improvement factor of about 8 at 805 MHz and 20 at 200 MHz. These are significant improvement factors and could greatly affect the economics of the factory or Collider.

Tanabe has also shown that the improvement factor is reduced greatly by the peak RF surface magnetic field in vacuum cavities. He speculates this is due to multipactoring as is the case for superconducting RF cavities. If Tanabe is correct, this effect will be absent from the high pressure gas cavity because the gas will suppress multipactoring. If the effect persists, this study will also perform experiments to determine its characteristics and possible remedies.

### Anticipated Benefits

High Energy Physics has relied on particle accelerators of the highest energy to discover and elucidate the fundamental forces of nature for much of the last century. The most likely path to the energy-frontier machine to follow the LHC (with quark-antiquark collision energy around 1.5 TeV) has yet to be determined. A muon collider is an attractive candidate machine. Muons are simple particles so that all of their collision energy is effective in creating new states of matter, and they are heavy enough to escape serious synchrotron radiation problems even in superconducting circular storage rings of considerable energy.

Linear electron- positron colliders are probably limited to about 1.5 TeV center-of-mass energy because of radiative processes. Proton colliders, because of the constituent nature of the proton, must have even higher energy and may require large amounts of politically sensitive real estate. However, a muon collider with nearly 10 TeV center-of-mass energy could fit on the present Fermilab site.

The very future of High Energy Physics and the search for understanding of the fundamental nature of the universe depends on finding a way to an energy-frontier machine. We believe that this proposal to create a new kind of RF cavity, which takes advantage of the unique properties of the muon, can make ionization cooling a more credible component of the muon collider concept. **Thus this project will contribute to the national and international planning for the next energy-frontier machine.**

A Neutrino Factory is an attractive first step toward a Muon Collider, especially since the requirements for ionization cooling for the Neutrino Factory are somewhat relaxed relative to the Muon Collider. Neutrino physics is extremely interesting at this time and there is considerable pressure to build such a machine.

The neutrino factory design studies conclude that an ionization-cooling channel costs about a third of a billion dollars and they conclude that the costs scale as the length of the channel. The length, in turn, is inversely proportional to the RF cavity gradient. If this proposed project is perfectly successful, we anticipate that the gradient can be increased a factor of 1.7, using the same RF power as in the studies. There will be additional costs due to the refrigeration and pressure systems, but the idea that the channel cost can be reduced by 33% is credible. In addition, since the cooling channel will be shorter, it will cool the muon beam more efficiently with fewer losses. Thus if this project is successful, we anticipate that **the construction cost for an improved ionization cooling channel of a neutrino factory can be reduced by over \$100M.**

## The Phase I Project

### a. Technical Objectives

The primary goal of Phase I is to build a test cell suitable for measuring the RF breakdown characteristics of gases to be used in ionization cooling applications. For Phase II, the test cell will be used for the exploration of Paschen's Law, relating breakdown voltages to gas density, over a range of temperatures, pressures, external magnetic fields, ionizing radiation, and gases. Determination of the high-voltage breakdown properties of helium gas using this RF test cell at room and liquid nitrogen temperatures will be a measure of the success of the Phase I project.

The optimization of the RF cavity design to be used for an ionization-cooling channel is the primary activity for Phase II of the project. The Phase I test cell is needed for this phase II optimization for two reasons. The first is to confirm and extend the measurements of gas characteristics relating to Paschen's Law. The second reason is to gain experience working in these new conditions. Pressurized, cryogenic RF cavities, as far as we know, have never been built before. Moreover, cryogenic copper RF cavities built to capitalize on lower resistivity do not show up in literature searches, even though there have been suggestions for this application.

Adding to these novel issues that we intend to explore is the use of a large quantity of hydrogen gas in extreme conditions. Thus, our approach will be to commission the test cell using nitrogen and helium gases to gain experience and confidence in the apparatus. Applying the knowledge gained in the actual testing of liquid hydrogen absorbers by NIU and IIT at Fermilab, we will be able to move on to the test measurements using cold, pressurized hydrogen gas as part of the phase II project.

The goal of the phase II project is to build a prototype of a 200 MHz cavity, as required by the demands of muon ionization cooling. However, time and availability constraints may dictate that the RF frequency used for the phase I test cavity may be something else. For example, there is an 800 MHz RF system in Lab G at Fermilab that would suit most of our phase I purposes and is operational now. Another test area which is under construction at the end of the 200 MeV Linac at Fermilab will have 200 MHz power available, but is unlikely to be available until 2003, the projected phase II time scale. This Linac test area will be ready in time for phase II tests and is scheduled to have all the additional requirements that we need, including hydrogen safety environment, external solenoidal field, and the 200 MeV $H^-$ Linac beam for radiation tests. In the same spirit as using nitrogen and helium before moving on to hydrogen, we can try working at 800 MHz for Phase I before moving on to 200 MHz. At this higher frequency we can take advantage of an available test set up and also facilitate the project because the components are smaller and easier to build, contain less gas, and are more readily available. For the Paschen curve characterisitics that we plan to investigate first, there should be a weak dependence on RF frequency.

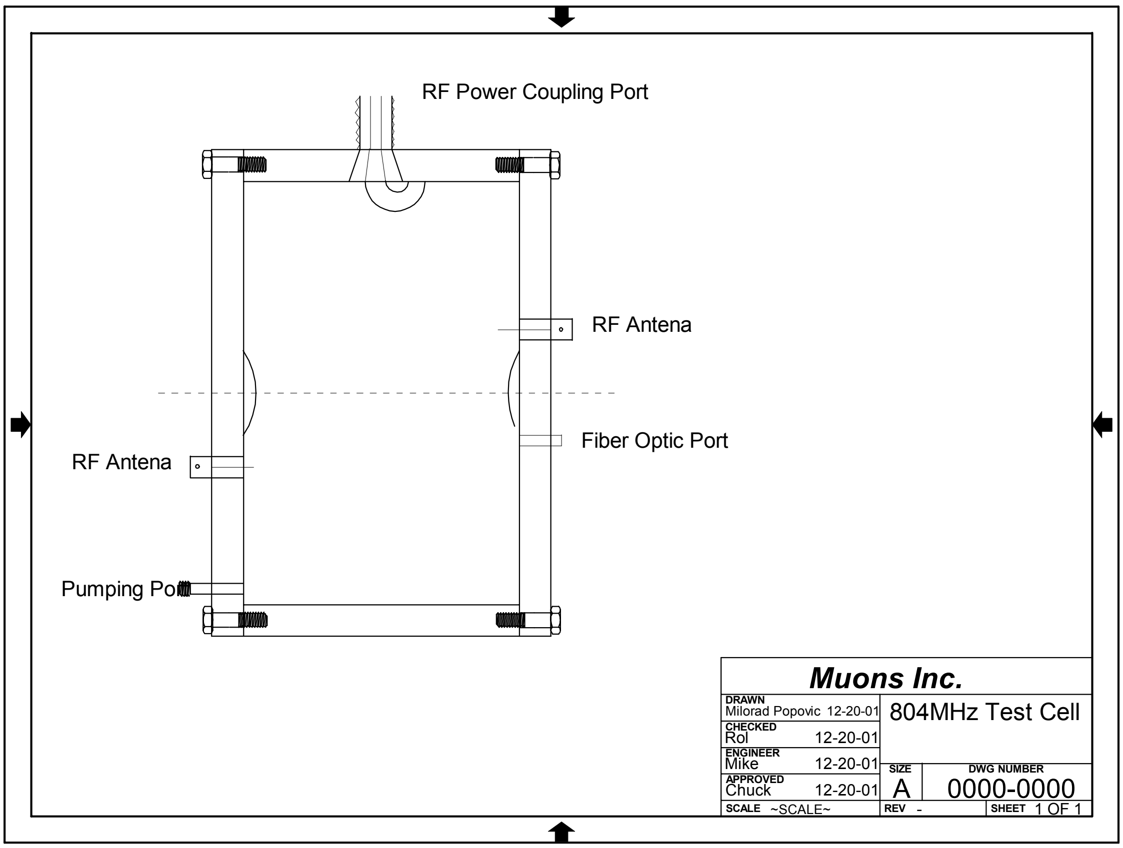
The Phase I test cell also will be used to determine the relationship between the power required by an RF cavity as a function of cavity temperature. The 200MHz test cell built during Phase II will be useful for unraveling the frequency dependence of effects like the anomalous skin depth.

## b. Phase I Work Plan

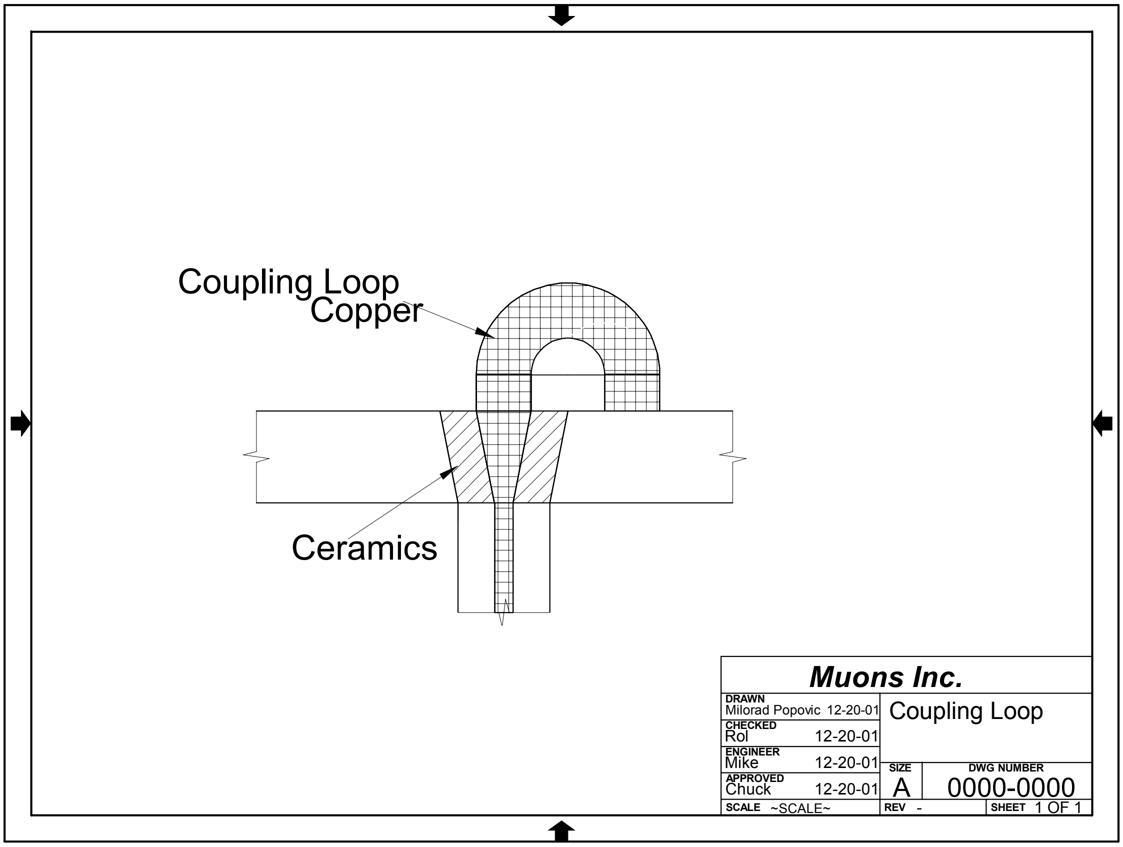
### Design of RF Test Cell

Work done by employees of Muon Inc., IIT, and consultants at Muon Inc. and at IIT.

The test cell will be a simple pillbox shape, probably with a coaxial RF feed. It will have a port to allow gas to be introduced and pumped out. The cell will be cooled by immersion in a cryogenic bath. Spherical surfaces on the cell axis will define the location of high voltage breakdown. The test cell must operate up to 100 atmospheres at temperatures down to 30k. Here is a sketch of a possible configuration of the test cell.




The design, construction, and testing of the high-voltage **RF feedthrough** for this cavity, needed for a wide range of operating conditions, is a major challenge of phase I. In the final design for a cooling channel, the RF feedthroughs are a major part of the gas containment system. The experience gained in this Phase I enterprise will be important to the final cooling channel design. The test cell feedthrough should operate from room temperature and pressure down to 30K and up to 100 atmospheres. It may be fed with coaxial line or a wave-guide. The present thinking, for the initial tests, is to use a coaxial line through a conical ceramic insert, where the diameter of the inner conductor decreases as the cone narrows to match the impedance of the coaxial line. Below is a sketch showing this matching. The conical shape is meant to provide a robust way to operate with the range of temperatures and pressures of phase II optimization investigations.




**Construction and Assembly of Test Cell**
Work done by employees of Muon Inc., IIT, and consultants at Muon Inc. and IIT.
The test cell is to be constructed in the IIT shops. It will be assembled, pressure tested, and RF bench tested at MUONS INC. and at Lab G at Fermilab.

**Operation of Test Cell**
Work done by employees of Muon Inc. and IIT at Muon Inc. and IIT. The RF measurements will be made using the apparatus available at Lab G at Fermilab. For completing the Phase I objectives, high-voltage breakdown as signified by reflected power from the test cell, will be measured for helium gas at various pressures for room and liquid nitrogen temperatures.

**Responsibilities**

**MUONS INC.**: The direction of the project is the responsibility of the company and the PI. The development of the computer representation of the RF test cell and the maintenance of the database of its scientific and engineering parameters will be the responsibility of Mr. Black. The assembly and operation of the test cell will be the responsibility of Mr. Hartline.

**IIT:** Since the results of this SBIR proposal will be appropriate for publication in scientific journals, Professors Kaplan and Cassel are participating in this work as part of their academic research. Their additional responsibilities to the Phase I project include the supervision and direction of postdoctoral researchers involved in collaborating on the development of the test cell. Part of the funds going to the IIT subcontract is for the support of these postdoctoral researchers. The other part of the IIT funding is for machine shop work on the construction of the RF test cell.

**Consultants:** The consultants, all employees of Fermilab, have a history of successful collaboration with the Principal Investigator. They will provide guidance in their particular areas of expertise as well as participate in the development of the test cell.

**Role of Fermilab:** Although Fermilab is not a subcontractor to this Phase I project, it supports this research. Steve Holmes, Associate Director for Accelerators and Steve Geer, spokeman for the MUCOOL experiment, have drafted a letter to this effect. It will be forwarded to Dr. Robert E. Berger, SBIR/STTR Program Manager. The use of the Lab G facilities to do the first measurements of the Paschen curve at liquid nitrogen pressures would be under the auspices of the collaboration of IIT and Fermilab.

**<u>Phase I Performance Schedule</u>**

Two months after start of funding
- RF feedthrough designed
- Test cell designed
- RF test facility identified and scheduled

Four months after start of funding
- Test cell constructed, assembled, and tested at low temperature and high pressure
- Identification of a small business partner for Phase II

Six months after start of funding
- Paschen curves measured for helium for the first time at LN2 temperatures
- Phase II proposal prepared

**c. Related Research or R&D**

**<u>Related SBIR Proposal under Topic 20b</u>**

MUONS INC. has submitted an independent SBIR proposal with complementary goals under technical topic 20b. The cooling channel itself is the major concern of the proposal under Topic 20b. The design and simulations necessary to understand a cooling channel based on a gaseous energy absorber are the primary concern. The goal is the development of a cooling channel design with virtues superior to the ones based on use of many liquid hydrogen energy absorbers. The designs and simulations will be carried out in such a way that developments in pressurized RF cavities can be easily incorporated.

**The two proposals, one under 21a and this one under 20b are complementary and do not duplicate work. They have no overlapping tasks. They are concerned with different technology.**

This RF cavity development proposal under 21a is a program of experimental investigations into the behavior of RF cavities filled with cold high-pressure gas in a magnetic field and exposed to charged-particle radiation. For example, this program will verify and extend the statements found in the literature regarding high-voltage breakdown and establish our ability to address safety concerns. Questions of power feedthroughs for high-pressure, cryogenic operation of RF cavities are a major part of the proposal. The ultimate goal is to develop the parameters for very high voltages in cavities used for ionization cooling.

**d. Principal Investigator and other Key Personnel**

**MUONS INC. Principal Investigator: Dr. Rolland P. Johnson** has been actively involved in particle accelerator research and development for over 25 years. He has worked on all aspects of synchrotrons, storage rings, and light sources at several institutions. Dr. Johnson has directed several successful accelerator R & D, construction, and commissioning projects. Examples include H- injection into the Fermilab Booster, new extraction kickers for the Booster, Booster RF cavity gradient improvement program, Tevatron low beta insertion, Tevatron Collider, and LSU light source. He directed many hardware projects at LBL, Fermilab, CAMD, and CEBAF. He also provided technical oversight to several SBIR grants while on detail to the DOE.

Dr. Johnson has considerable experience in the area of RF systems for particle accelerators. He has participated in several RF hardware efforts, including 30-53 MHz systems of the Fermilab Booster, the 53 MHz systems of the Main ring and Tevatron, and the 500 MHz system of the LSU CAMD synchrotron light source. More recently he has been involved in activities associated with The Neutrino Factory and Muon Collider Collaboration[xix]. Besides work on methods to increase the proton flux for better muon production as seen in the Proton Driver Design Report and The Linac Afterburner Proposal, he has worked on improving ionization cooling. An abbreviated C.V., with some relevant publications follows.

**MUONS INC. Design Engineer: Edgar Black** (BS Physics and Math 1955, MS Civil Engineering 1959) has worked at Argonne (1976-1985, 1990-1998), Fermilab (1985-1990), and at IIT (1998-2002) as a design and project engineer on many diverse projects. He has extensive experience on projects requiring expertise in mechanical, chemical, civil, and electrical disciplines. At Argonne he was responsible for managing the construction of over 1070 electromagnets for the Advanced Photon Source. Most recently he has been heavily involved in the engineering of the cooling channel designs based on liquid hydrogen energy absorbers. At the time of the SBIR grant he will be an employee of MUONS INC.

**MUONS INC. RF Engineer: Robert Hartline** worked with Dr. Johnson on the design, installation, commissioning, and development of the CAMD light source. He has agreed to be an employee of MUONS INC. for the development of pressurized RF cavities for ionization cooling.

**IIT Subcontract PI: Professor Daniel M. Kaplan**, a leader in High Energy Physics for many years, has become a strong advocate for accelerator research in universities. He is the Principal Investigator for the $2.5M/year State of Illinois grant to the Illinois Consortium for Accelerator Research (ICAR) to promote accelerator physics in five universities associated with Fermilab. He has taken a leading role in the Neutrino Factory and Muon Collider Collaboration as a member of both the Technical and Executive Boards. Recently he has become the US leader of the International Muon Cooling Experiment (MICE). An abbreviated C.V., with some relevant publications is below.

**IIT Mechanical Engineer: Professor Kevin Cassel** is a member of the faculty of the Mechanical, Materials, and Aerospace Engineering Department at the Illinois Institute of Technology. His expertise is in computational fluid dynamics (CFD) and he has been involved in a wide variety of research projects ranging from unsteady aerodynamics to buoyancy-driven flows. For more than two years he has conducted research to aid in the design of the liquid-hydrogen absorbers proposed for use by the Neutrino Factory and Muon Collider Collaboration. He will be working with Dr. Aleksandr Obabko, who received his Ph.D. in Mechanical and Aerospace Engineering from IIT in December 2001.

**Consultant Accelerator Physicists: Dr. Charles M. Ankenbrandt and Dr. Milorad Popovic** have worked with Dr. Johnson on many projects. Most recently they have worked together on proton driver issues for a neutrino factory, including a proposal to upgrade the Fermilab Linac to improve the operation of the existing Fermilab accelerator complex.

**Consultant Materials Specialist: Moyses Kuchnir** has worked at Fermilab for over 27 years on many diverse projects. He has been a contributer to the development of the superconducting magnets for the Tevatron and the SSC.

**Consultant RF Engineer: Alfred Moretti,** also a Fermilab veteran, has been involved in many RF projects. At present, he is directing the Lab G RF test area.

# C.V.

*Name:* **Rolland P. Johnson**

*Address:* 45 Jonquil Lane, Newport News, VA 23606
(757) 930-1463 Roljohn@aol.com

*Academic Background:* U. of California, Berkeley Ph.D., Physics, June 1970
U. of California, Berkeley AB, Mathematics, June 1964

*Work Experience:* Particle accelerator design, construction, operation, and controls. Project Management. DOE funding of R and D. Experimental High Energy Physics Research. Teaching.

*Employment Background:*

1996-present Consultant
Consulting contracts with CAMD, Fermilab, DOE, DESY, SRRC, IIT (active)

1993-1996 Senior Staff Scientist, Jefferson National Accelerator Facility, (CEBAF)
(94-96) On Detail to DOE Headquarters, Germantown MD. Program monitor for 11university grants. Acting Technical Topic monitor for 12 SBIR grants. Project reviewer. Member SSC equipment reallocation team.
(93-94) Head of Instrumentation and Controls Department, CEBAF Accelerator Division, Responsible for Control, Beam Instrumentation, and Safety Systems. Program coordinator for machine commissioning

1991-1992 Senior Accelerator Physicist, MAXWELL LABS, Brobeck Division
In charge of installation and commissioning the 1.4 GeV CAMD light source at LSU

1974-1991 Physicist, FERMI NATIONAL ACCELERATOR LABORATORY
(84-91) Tevatron Coordinator for Collider upgrades. Responsible for design, debugging of low beta inserts, e-s beam separation, diagnostics. Invented “double-helix” beam separation scheme. Supervised software development. Wrote design programs for RF systems and lattice insertions. Directed machine commissioning.
(90-92) Adj. Professor, NIU. Taught "Introduction to Particle Accelerators".
(88-92) CDF Experimenter, responsible for CAMAC system, alarms and limits and high voltage control, and integration of the experiment into the accelerator control system. Contributor to luminosity and total cross-section analyses.
(88-91) Chairman, Wilson Fellows Committee to recruit, select, nurture extraordinary physicists. Thesis supervisor for two Ph. D. students. Directed experimental accelerator research using the Tevatron.
(83-84) Leader of a Tevatron commissioning team. Also wrote programs to control RF, excitation ramps, correction elements, closed orbit, monitor of cryogenics, vacuum.
(82-83) Member of antiproton source design group. Coordinated the original design report. Specified energy, location, and stochastic cooling systems. Wrote RF control programs.

- (80-82) Assignment to CERN, Geneva, Switzerland. Participated in commissioning and initial operation of the Anti-proton Accumulator. Wrote the RF control programs. Improved 1 to 2 GHz stochastic cooling systems.
- (79-80) Assistant Head of Accelerator Division, in charge of Linac, Booster, Main Ring, Switchyard and Operations Groups. Directed the activity of about 250 people to operate and improve the accelerator fixed target program. Had record intensity levels and reliability.
- (78-79) E203 experimenter. Leader of a group of Fermilab physicists who collaborated with Princeton and Berkeley to study deep inelastic muon scattering.
- (75-78) Leader of Booster Synchrotron Group. In charge of the development and operation of the 8 GeV rapid cycling synchrotron. Increased output current by a factor of 3. Built fast bunch-by-bunch transverse dampers to control head-tail instabilities. In charge of $H^-$ injection project. Directed RF cavity development projects.
- (74-75) Member, Main Ring group. Responsible for high field closed orbit of the 400 GeV MR synchrotron. In charge of the 8 GeV transfer line between Booster and MR.

1963-1974 Physicist, LAWRENCE BERKELEY LABORATORY

- (70-74) Postdoctoral Research Associate. Bevatron experiments: muon neutrino mass limit, muon range differences, and Kl3 form factors from muon polarization.
- (72-73) Visiting Scientist IHEP, Serpukhov, USSR. Experiments at the 70 GeV synchrotron on pion-proton interactions. Discovered $h^o$ meson. Worked in a Russian group.
- (67-70) Graduate Student Research Asst. Ph.D. thesis experiment on rare decays of the neutral K-meson at the Bevatron.
- (63-67) Research Apparatus Operator. Programmer, data analyst.

*PERSONAL:* Conversational Russian and French, tennis, piano, guitar, sailing, woodworking.

## Publications

**Over 50 references to publications in Accelerator Topics and over 80 in High Energy Physics can be found at http://members.aol.com/roljohn. Some work relevant to this proposal:**


A GASEOUS ENERGY ABSORBER FOR IONIZATION COOLING OF MUON BEAMS. Rolland Johnson and Daniel M. Kaplan, MUC/NOTE/COOL_EXP/PUBLIC/195 March, 2001

COST AND PERFORMANCE OF RAPID-CYCLING PROTON SYNCHROTRONS, C. M. Ankenbrandt and R. P. Johnson, Proceedings of the 2001 Particle Accelerator Conference, http://pacwebserver.fnal.gov/papers/Thursday/PM_Poster/RPPH039.pdf.

A LINAC AFTERBURNER TO SUPERCHARGE THE FERMILAB BOOSTER, C. M. Ankenbrandt, J. MacLachlan, M. Popovic, and R. P. Johnson, July, 2001. http://www-dnew.fnal.gov/proton_source/popovic/work/AnotherFNALinacEnergyUpgrade.doc.

PROGRESS IN ABSORBER R & D FOR MUON COOLING, D.M. Kaplan, et al., IIT-HEP-01-1, Aug 2001. 7pp. 3rd International Workshop on Neutrino Factory based on Muon Storage Rings (NuFACT'01), Tsukuba, Japan, 24-30 May 2001. e-Print Archive: physics/0108027

SYNCHRONIZING THE PROTON BEAM RF WITH THE MUON COOLING RF. Charles M. Ankenbrandt and Rolland Johnson, MUC/NOTE/COOL_EXP/PUBLIC/97, March 2000.

COMMISSIONING OF THE SYNCHROTRON LIGHT SOURCE AT LSU. R.P.Johnson, et al. Berlin:EPAC 1992:197.

COMMISSIONING OF THE CAMD LSU 200 MEV ELECTRON LINAC INJECTOR. P. Letalier, et al. Berlin:EPAC 1992:575.

MEASURING AND MANIPULATING AN ACCUMULATED STACK OF ANTI-PROTONS IN THE CERN ANTIPROTON ACCUMULATOR. R. Johnson, S. van der Meer, and F. Pederson, IEEE Trans. Nucl. Sci.NS-30 No. 4, (1983) 2123.

COMPUTER CONTROL OF RF-MANIPULATIONS IN THE CERN ANTIPROTON ACCUMULATOR. R. Johnson, S. van der Meer, F. Pederson and G. Shering, IEEE Trans. Nucl. Sci. NS-30 No. 4,(1983)2290.

RECENT EXPERIENCE WITH ANTIPROTON COOLING. G. Carron, R. Johnson, S. van der Meer, C. Taylor and L. Thorndahl, IEEE Trans. Nucl. Sci. NS-30 No. 4, (1983) 2587.

THE FERMILAB ANTIPROTON SOURCE DESIGN REPORT, J. Peoples et al., (Feb. 1982).

STOCHASTIC STACKING WITHOUT FILTERS. Rolland P. Johnson & John Marriner, FERMILAB-Pub-82/92 (Dec. 1982) BNL Beam Cooling Wkshp.1982: (QCD183:W65:1982).

# C.V.

**Daniel M. Kaplan**
Professor of Physics
Illinois Institute of Technology
3101 S. Dearborn Street
Chicago, IL 60616

Telephone: (312) 567-3389
Email: kaplan@fnal.gov

**Education:**

| | | | |
|---|---|---|---|
| Haverford College | Physics | B.A. | 1974 |
| SUNY at Stony Brook | Physics | Ph.D. | 1979 |

**Positions:**

| | | |
|---|---|---|
| Professor | Illinois Institute of Technology | 2001- |
| Associate Professor | Illinois Institute of Technology | 1994-2001 |
| Associate Professor | Northern Illinois University | 1990-94 |
| Assistant Professor | Northern Illinois University | 1987-90 |

**Other Academic Experience:**

| | | |
|---|---|---|
| Research Associate | Columbia University Nevis Laboratories | 1978-82 |
| Associate Scientist | Fermi National Accelerator Laboratory | 1982-84 |
| Staff Scientist | Physics Dept., Florida State University | 1984-86 |
| Guest Scientist | Beams Division, Fermilab | 1998-99 |
| Guest Scientist | Beams Division, Fermilab | 1999-2000 |

**Funding:**

| | |
|---|---|
| DOE grants to the HEP group, Northern Illinois University | 1987-94 |
| DOE grants to the HEP group, Illinois Institute of Technology | 1994- |
| Grants from the Muon Collaboration via Fermilab for LH2 Absorber R&D | 1998-2000 |
| NSF subcontract to ICAR via Cornell | 2000-01 |
| Technology Challenge Grant to ICAR, Illinois DCCA | 2000-02 |
| HECA grants to ICAR, Illinois Board of Higher Education | 2000-02 |

**Professional Service:**

| | |
|---|---|
| Co-spokesman, Fermilab Experiment 789 | 1988- |
| Leader, Illinois Institute of Technology HEP group | 1994- |
| Co-leader, Trigger/DAQ Working Group, BTeV Collaboration | 1997- |
| Member, Fermilab Steering Group, Muon Collaboration | 1999- |
| Member, Muon Collaboration Executive Board | 1999- |
| Member, Muon Collaboration Technical Board | 2000- |
| Principal Investigator, Illinois Consortium for Accelerator Research (ICAR) | 2000- |

**Teaching Experience:**

More than 25 courses:

- Undergraduate courses: introductory physics, mathematical methods, mechanics, modern physics, analog and digital electronics laboratories developed specifically for engineering students, physics majors, and science majors

- Graduate courses: elementary particle physics

**Publications:**
Co-author of more than 150 publications in refereed journals, conference proceedings, and other reports; co-editor of three books.

**Five publications most closely related to this proposal:**
D. M. Kaplan and K. S. Nelson, *Introduction to Subatomic-Particle Spectrometers*, Wiley Encyclopedia of Electrical and Electronics Engineering, J. G. Webster, ed., Wiley, New York, 1999, p. 662.

J. C. Gallardo et al., *An Ionization Cooling Channel for Muon Beams Based on Alternating Solenoids*, Proc. 1999 Particle Accelerator Conference, A. Luccio, W. MacKay, eds., IEEE, New York, 1999, p. 3032.

D. M. Kaplan, *Muon Collider/Neutrino Factory: Status and Prospects* (invited talk), to appear in Proc. 7th International Conference on Instrumentation for Colliding-Beam Physics, Hamamatsu, Japan, Nov. 15-19, 1999.

T. Anderson et al., *A Feasibility Study of a Neutrino Source Based on a Muon Storage Ring*, Fermilab -Pub-00-108-E, June 2000, submitted to Phys. Rev. ST Accel. Beams.

D. M. Kaplan et al., *Energy Absorber R&D,* to appear in Proc. 2nd International Workshop on Neutrino Factories based on Muon Storage Rings (NuFACT '00), Monterey, CA, May 22-26, 2000.

**e. Facilities/Equipment**.
MUONS INC. presently occupies a building of approximately 4000 square feet of floor space in Batavia, Illinois, a short drive to Fermilab. This building can be partitioned as office space, conference rooms, and living quarters as needed. As this grant proposal represents the start of MUONS INC. as a profit making organization, the facilities are minimal, but adequate for Phase I of the proposed project. The development of designs and the analysis of data require knowledgeable people, places to meet, computers for simulations and CAD/CAM, and access to libraries and the web. The hardware construction will be at IIT and testing will be at Fermilab.

**f. Consultants and Subcontractors**
**(i) Research Institution**
The research institution is the Illinois Institute of Technology
**(ii) Other Consultants and Subcontractors**
Dr. Charles M. Ankenbrandt, Dr. Milorad Popovic, Dr. Moises Kuchnir and Alfred Moretti have agreed to act as consultants on this project. Letters of Commitment are shown below.

## Consultant Letters of Commitment

## Similar Grant Applications, Proposals, or Awards

We have submitted no similar grant applications or proposals. We have received no awards for this project.

## References

[i] *Neutrino beams from muon storage rings: Characteristics and physics potential,* S. Geer, PRD 57, 6989 (1998);

[ii] *Status of muon collider research and development and future plans,* C. M. Ankenbrandt et al., Phys. Rev. ST Accel. Beams 2, 081001 (1999).

[iii] http://www.cap.bnl.gov/mumu/mu_home_page.html

[iv] *Feasibility Study on a Neutrino Source Based on a Muon Storage Ring*, D. Finley and N. Holtkamp ed., March 2000
http://www.fnal.gov/projects/muon_collider/nu-factory/fermi_study_after_april1st/

[v] *Feasibility Study II of a muon based neutrino source*, S. Ozaki et al., available from http://www.cap.bnl.gov/mumu/studyii/FS2-report.html

[vi] *Prospective study of muon storage rings at CERN*, B. Autin, A. Blondel and J. Ellis eds, CERN yellow report CERN 99-02, ECFA 99-197;
*Current Activities for a Neutrino Factory at CERN*, R. Garoby,
CERN-PS-2001-007-RF NuFact Note 74,
available from http://muonstoragerings.web.cern.ch/muonstoragerings ;
*The Study of a European Neutrino Factory Complex,* B. Autin et al., NuFact Note 103 (Dec 2001).

[vii] http://proj-bdl-nice.web.cern.ch/proj-bdl-nice/cool/loi/final_loi.doc

[viii] MUCOOL Note 190 V. Balbekov

[ix] A GASEOUS ENERGY ABSORBER FOR IONIZATION COOLING OF MUON BEAMS, Rolland Johnson and Daniel M. Kaplan, MUC/NOTE/COOL_EXP/PUBLIC/195 March, 2001

[x] MUCOOL Note 190 V. Balbekov

[xi] 3 D.R. Lide, editor, Handbook of Chemistry and Physics, 77th ed. 1996-1997, p.12-40

[xii] http://home.earthlink.net/~jimlux/hv/paschen.htm
http://home.earthlink.net/~jimlux/hv/hvmain.htm contains many useful facts.

[xiii] Meek and Craggs, **Electrical Breakdown in Gases**, John Wiley & Sons, 1978, p. 557. Note that experimental data extend only to about 25 atmospheres.

[xiv] http://www.slac.stanford.edu/grp/arb/tn/arbvol1/ARDB042.pdf

[xv] G. R. H. Reuter, E.H. Sondheimer, Proc. Roy. Soc. A195 (1948) 336

[xvi] A.F. Harvey, "Microwave Engineering", Academic Press, London and New York, 1963, pp259-261.

R. G. Chambers, "The anomalous Skin Effect", Proc. Roy. Soc., 1952, 215A, p. 481.

[xvii] R. G. Chambers, "The Effect of Relaxation on Microwave Measurement of Anomalous Skin Effect", Physica, 1953, 19, p. 365.

[xviii] A. H. McEuen, P. Lui, E. Tanabe, "High Power Operation of Accelerating Structures at Liquid Nitrogen Temperature", IEEE Trans Nucl Science, 1985, NS-32, 5, p.2972.

[xix] http://www.cap.bnl.gov/mumu/mu_home_page.html

DOE F-4620.3
(09-90)

APPENDIX C

U.S. DEPARTMENT OF ENERGY

# SMALL BUSINESS INNOVATION RESEARCH (SBIR) AND SMALL BUSINESS TECHNOLOGY TRANSFER (STTR) GRANT APPLICATION BUDGET

*(Please Print or Type)*

FIRM NAME: **MUONS INC.**

| A. PERSONNEL *(Employees)* NAME | ROLE IN PROJECT | EST. HOURS | HOURLY RATE | FRINGE BENEFITS | TOTAL COST |
|---|---|---|---|---|---|
| Dr. Rolland P. Johnson | Principal Investigator | 250 | 60 | 20 | 20000 |
| Edgar Black | Design Engineer | 250 | 50 | 16.67 | 16667 |
| Robert Hartline | RF Engineer | 250 | 50 | 16.67 | 16667 |

| B. CONSULTANTS NAME | ROLE IN PROJECT | EST. HOURS | HOURLY RATE | | TOTAL COST |
|---|---|---|---|---|---|
| Dr. Charles M. Ankenbrandt | Accelerator Physicist | 40 | 60 | | 2400 |
| Dr. Moyses Kuchnir | Materials Specialist | 40 | 60 | | 2400 |
| Dr. Milorad Popovic | Accelerator Physicist | 80 | 50 | | 4000 |
| Alfred Moretti | RF Engineer | 80 | 50 | | 4000 |

| | |
|---|---|
| C. LEASED EQUIPMENT *(Specify Time and Rate, or Other Basis)* ITEM | 0 |
| D. PURCHASED EQUIPMENT ITEM / AMOUNT<br>RF test cell components, RF feedthrough materials, gauges | 8000 |
| E. TRAVEL | 0 |
| F. OTHER DIRECT COSTS<br>1. Materials and Supplies<br>2. Publication Costs<br>3. Testing Services (Including work at Government Installations)<br>4. Computer Services<br>5. Research Institution ........ 33000<br>6. Other Subcontracts<br>7. Other<br>TOTAL OTHER DIRECT COSTS | 33000 |
| G. TOTAL DIRECT COSTS *(A through F)* | 107137 |
| H. INDIRECT COSTS *(Specify Rate and Base)*<br>TOTAL INDIRECT COSTS | 0 |
| I. TOTAL COSTS *(G plus H)* | 107137 |
| J. FEE OR PROFIT | 10714 |
| Subtotal *(I plus J)* | 117851 |
| K. COST SHARING Provided by MUONS INC. | 17851 |
| L. TOTAL AMOUNT OF THIS REQUEST *(Item I plus J minus K)* | 100000 |

M. Has any executive agency of the United States Government performed any review of your accounts or records in connection with any other grant or contract within the past year? Yes Ξ No. If Yes, give name, address, and phone number of reviewing office and official:

N. CORPORATE/BUSINESS AUTHORIZED REPRESENTATIVE - TYPED NAME AND SIGNATURE DATE:

Linda L. Even

(Signature)

# APPLICATION CHECKLIST

**APPENDIX D**

(Not Counted in the 25-page Limitation)

| |
|---|
| Firm Name: MUONS INC. |
| Project Title: Pressurized RF Cavities for Muon Ionization Cooling |

Please complete both sides of the checklist and paper clip (one copy only) to the cover sheet of the original (signed) copy of the grant application.

**DOES THE APPLICATION SATISFY THE FOLLOWING REQUIREMENTS:**

| | | Yes | No |
|---|---|---|---|
| T | One, and only one, topic from the Technical Topics Section identified on the cover page. | | |
| T | One, and only one, subtopic from the Technical Topics Section identified on the cover page. | | |
| T | All certifications on cover page completed and signed. | | |
| T | Principal Investigator will work a minimum of 5 hours per week on the project. (This corresponds to a total minimum of 130 hours for SBIR and 195 hours for STTR). * | | |
| T | All certifications and questions on cover page marked Y (yes) or N (no). | | |
| T | Amount requested not in excess of $100,000; if total on line L on the budget form exceeds $100,000, the application must explain who will contribute the difference. | | |
| T | Abstract contains no proprietary information and does not exceed space provided on the Project Summary Page (Appendix B). | | |
| T | Main text (technical content) is included as requested in Section 3.3. | | |
| T | Application, including all enclosures, not more than 25 pages. However, this checklist (Appendix D) and the Documentation of Multiple Phase II Awards (Section 3.3.7) will not be included in the 25-page count. | | |
| T | No font smaller than 12 point times new roman. | | |
| T | No pages other than 8 1/2" x 11". | | |
| T | Level of effort in compliance with Section 3.3.5a. (For SBIR, the small business must perform at least 2/3 of the research and analytical effort. For STTR, the small business must perform at least 40% and the research institution must perform at least 30%.) * | | |

* For grant applications that are to be considered for both SBIR and STTR, prepare the grant application to meet the requirements of the SBIR program. If the application is selected for STTR, scheduling or budgetary adjustments can be completed during the negotiation period before the grant begins.

***ATTENTION:*** ***GRANT APPLICATIONS NOT MEETING ALL OF THE ABOVE REQUIREMENTS WILL BE DECLINED WITHOUT FURTHER ACTION.***

## STATISTICAL INFORMATION

| | Yes | No |
|---|---|---|
| The proposing firm certifies that it is a socially and economically disadvantaged small business concern. (See Section 2.4.) | | |
| The proposing firm certifies that it is a women-owned small business concern. (See Section 2.5.) | | |

# WORKSHEET

For calculating the percent of the research and analytical effort performed by the small business, the research institution, if any, and other consultants or subcontractors (see Section 3.3.5.a.)

| | **Small Business** | **Research Institution (if any)** | **Other Consultants and/or Subcontractors** | **TOTAL** |
|---|---|---|---|---|
| **(1) Total Value of Project** | 72051 | 33000 | 12800 | ***(line I + line J from budget page*** 117851 |
| **(2) Value of leased, purchased, or in-kind equipment, and materials & supplies** | ***(lines C+D+F1 from budget page*****)** 8000 | **(Applicable portion of Research Institution=s subcontract)** 0 | **(Applicable portion of consultant and/or other subcontracts)** 0 | *** (See note below)** 8000 |
| **(3) = (1) - (2) Research or analytical effort (before applying cost sharing)** | 64051 | 33000 | 12800 | 109851 |
| **(4) Percentages before applying cost sharing (Divide entries on line (3) by total for line (3).)** | 58 | 30 | 12 | 100 |
| **(5) Cost Sharing , if any (Distribute in most favorable manner.)** | 0 | 5051 | 12800 | ***(Line K from budget page)*** 14549 |
| **(6) = (3) - (5) Research or analytical effort (after applying cost sharing)** | 64051 | 27949 | 0 | *** (See note below)** 92000 |
| **(7) Percentages (Divide entries on line (6) by total for line (6).)** | 70 | 30 | 0 | 100 |

* NOTES: (1) The total of the two boxes marked A*≅ is the amount requested from DOE, Line L from the budget page. (2) This worksheet includes cost sharing, however, **cost sharing is not a requirement and has no effect on the evaluation of a Phase I grant application.**